Virtual window telepresence system for telerobotic inspection

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ABSTRACT

Telerobotic inspection can be used in environments that are too hazardous, removed or expensive for direct human inspection. Telerobotic inspection is a complex task requiring an operator to control and coordinate a robot and sensors, while monitoring and interpreting sensor data to detect flaws. A virtual window telepresence system has been developed to aid the operator in performing these inspections. While the operator is looking at a monitor displaying stereo video from cameras mounted on the robot, the system tracks operator head position and moves the robot to create the illusion that the operator is looking out a window. This interface allows the operator to naturally specify desired viewpoint and enables them to concentrate on the visual examination of the area that may contain a flaw.

Keywords: telepresence, telerobotics, inspection, virtual environments

1 INTRODUCTION

Space platforms operate in a very severe environment and need to be periodically inspected for the effects of micro-meteorites, radiation, extreme temperatures, etc.[1] Engineering reviews of the proposed space station have found that inspection and maintenance may consume more time than astronauts will have available.[2] Telerobotic inspection, either from inside the platform or from the ground, is an alternative to expensive Extra Vehicular Activities (EVA) by astronauts.

The Remote Surface Inspection (RSI) project at the Jet Propulsion Laboratory (JPL), California Institute of Technology has been developing technologies to automate the inspection process and facilitate telerobotic inspection.[3-5] It has developed an operator interface that integrates aspects of planning, control and sensing required for telerobotic inspection.[6-8] To test and demonstrate these capabilities, it controls a 7 degree of freedom

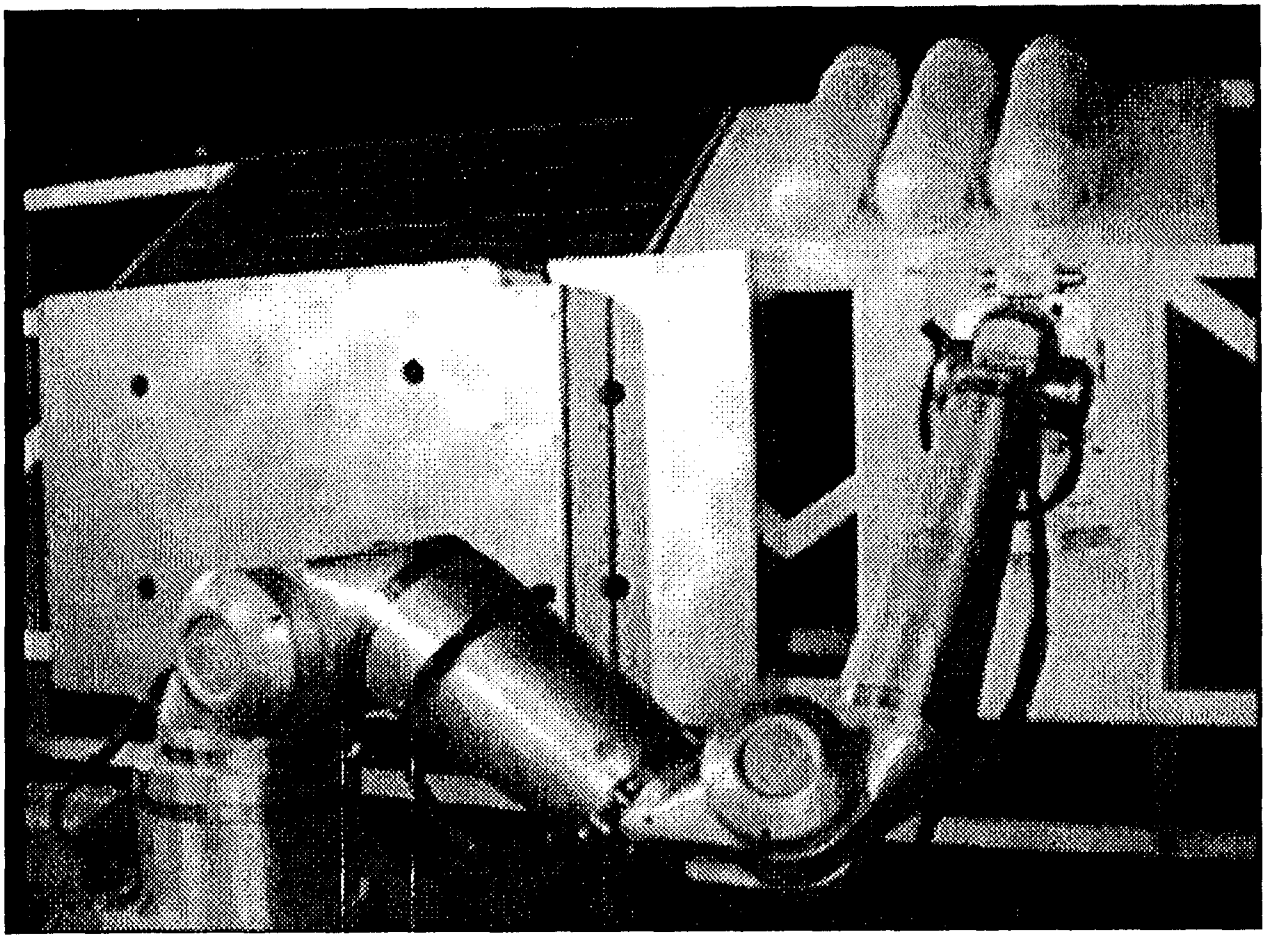

Figure 1: Remote Surface Inspection Laboratory

Robotics Research Corp. 1207 robot mounted on a rail to position an integrated sensor end effector to perform multi-sensor inspection of a one third scale mockup of a space station truss assembly (Figure 1).[9,10] The end effector includes a pair of cameras configured for stereo video and used for human and machine visual inspection. The interface provides for manual and autonomous control of the robot and manual and autonomous inspection. Once a potential flaw has been detected either by an operator or an automated inspection system, someone must examine the area of the potential flaw to verify and characterize it. This is usually done by the operator taking manual control of the robot and positioning the cameras with joysticks to view the area from different locations. It is for this examination that a virtual window telepresence capability has been integrated into the interface. The goal of the virtual window telepresence system is to free the operator from explicit control of the robot and allow him/her to concentrate on examination of the potential flaw.

2 VIRTUAL WINDOW

2.1 Approach

The area that needs to be examined for an individual flaw is typically small. The operator needs to observe this localized area from different viewpoints. To aid the operator performing the examination, we create a virtual window near the area of the flaw. The examination is done by the operator "looking through" this virtual window. The **view** through the virtual window appears on a stereo video monitor in the operators console. By tracking the operator's head position as they look at the monitor and moving the robot in a coordinated manner, the virtual window system creates the illusion that the monitor is a real window located at the position of the virtual window. This provides a feeling of telepresence as if the operator had "flown" the console and themselves to the inspection site. The benefit of this is that the operator has a natural interface to specify the desired view of the flaw area through the virtual window. in the presence of large time delays, we can also create a window into our graphical model of the environment to control a stereo graphic display. The operator could then specify a viewpoint with reference to the model and view the video returned once the remote site positioning has been accomplished.

2.2 Implementation

2.2.1 Equipment

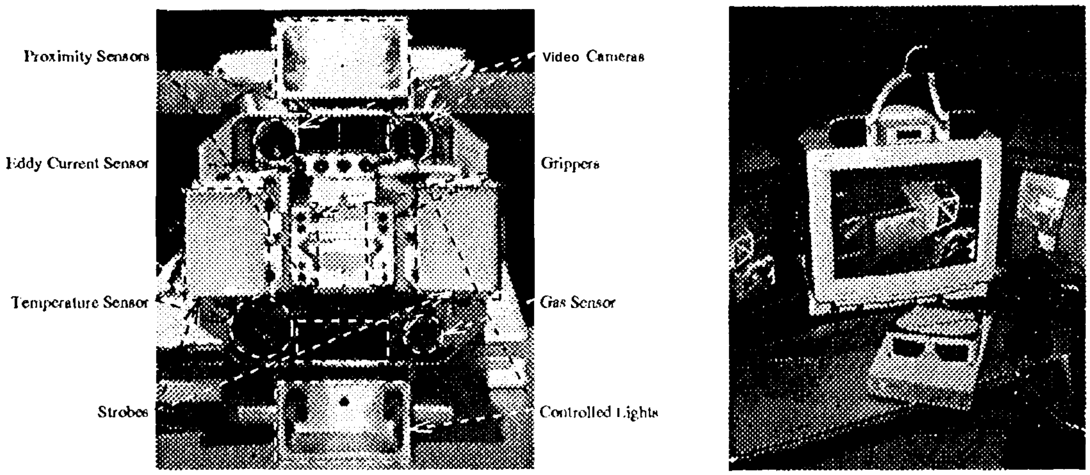

Figure 2: Virtual Window Hardware

To implement the virtual window, stereo video is provided by a pair of Toshiba IK-M41A cameras mounted on the end effector of the robot. The cameras are mounted 7 cm apart and are converged at 77 cm.[11] 7.5 mm lenses provide a 47 degree field of view. (Figure 2 left) The cameras are connected to a CrystalEyes Video view/record unit which drives a 13 inch VGA monitor at 120 Hz; 60hz for each eye. The monitor is viewed wearing CrystalEyes Eyewear which consists of an LCD shutter for each eye synchronized to the monitor with an infrared emitter. Head position relative to the monitor is measured using the Logitech 6 DOF acoustic tracking system that is part of the CrystalEyes VR product. The receivers are built into the CrystalEyes Eyewear and the transmitters are on a triangular frame on top of the monitor. (Figure 2 right) An RS-232 serial connection provides tracking information to the control computer, a Silicon Graphics 4D-310 VGXT.

2.2.2 Algorithm

The head frame relative to the stereo monitor ($^H_M F$) is measured by the tracking system. From this frame we construct the desired end effector (camera) frame relative to the virtual window ($^E_V F$). The desired orientation of the cameras is the yaw and pitch relative to the virtual window necessary to have the cameras point at the virtual window. The rotation matrix for this orientation is calculated from the measured head position vector as:

$$^E_V R_{yp} = \begin{bmatrix} cy & sysp & sycp \\ 0 & cp & -sp \\ -sy & cysp & cycp \end{bmatrix} \tag{1}$$

where:

$$sy, sin(yaw) = \frac{^H_M p_x}{\sqrt{^H_M p_x^2 + {^H_M p_z^2}}}$$

$$cy, cos(yaw) = \frac{^H_M p_z}{\sqrt{^H_M p_x^2 + {^H_M p_z^2}}}$$

$$sp, sin(pitch) = \frac{-{^H_M p_y}}{\sqrt{^H_M p_x^2 + {^H_M p_y^2} + {^H_M p_z^2}}}$$

$$cp, cos(pitch) = \frac{\sqrt{^H_M p_x^2 + {^H_M p_z^2}}}{\sqrt{^H_M p_x^2 + {^H_M p_y^2} + {^H_M p_z^2}}}$$

It should be noted that the orientation of the operators head is not used at all to calculate the desired camera frame. Views through a window are constrained by the relative position of the window and the eyes. If the head is oriented to look away from the window the view through the window for that position would not and should not change.

Calculating the desired position vector of the end effector relative to the virtual window is complicated by the fact that we are using fixed focal length cameras. When looking at objects through a real window, as you move your eyes closer to the window, your field of view through the window increases. The apparent size of objects on the other side of the window also increases. Had we been able to use controllable zoom lenses, we would have used a simple unity mapping of relative head position to relative end effector position and adjusted the focal length of the lenses so that the field of view of the cameras matched the angle subtended by the monitor to the eye. However, the current end effector contains fixed focal length cameras. Given this limitation, we are able to produce a mapping such that objects a given fixed distance behind the virtual window will appear fixed in space at a constant size. The appearance of objects further or closer than this distance will undergo a distortion that may be perceived as the object shrinking or growing in size or moving closer to or further from the operator as the operator moves further or closer to the monitor.

An object of size (r_o) a distance (d_o) behind a screen of size (r_s) a distance (d,) from the eye would have an apparent size (r_a) on the screen (Figure 3B). A camera a distance (d_c) from a virtual window with a field of view (γ) looking at the same object will image an area of size (r_c) at the depth of the object (Figure 3C). Since the area that he camera images will be displayed on the monitor screen, for the object to appear to remain a constant size:

$$\frac{r_a}{r_s} = \frac{r_o}{r_c} \tag{2}$$

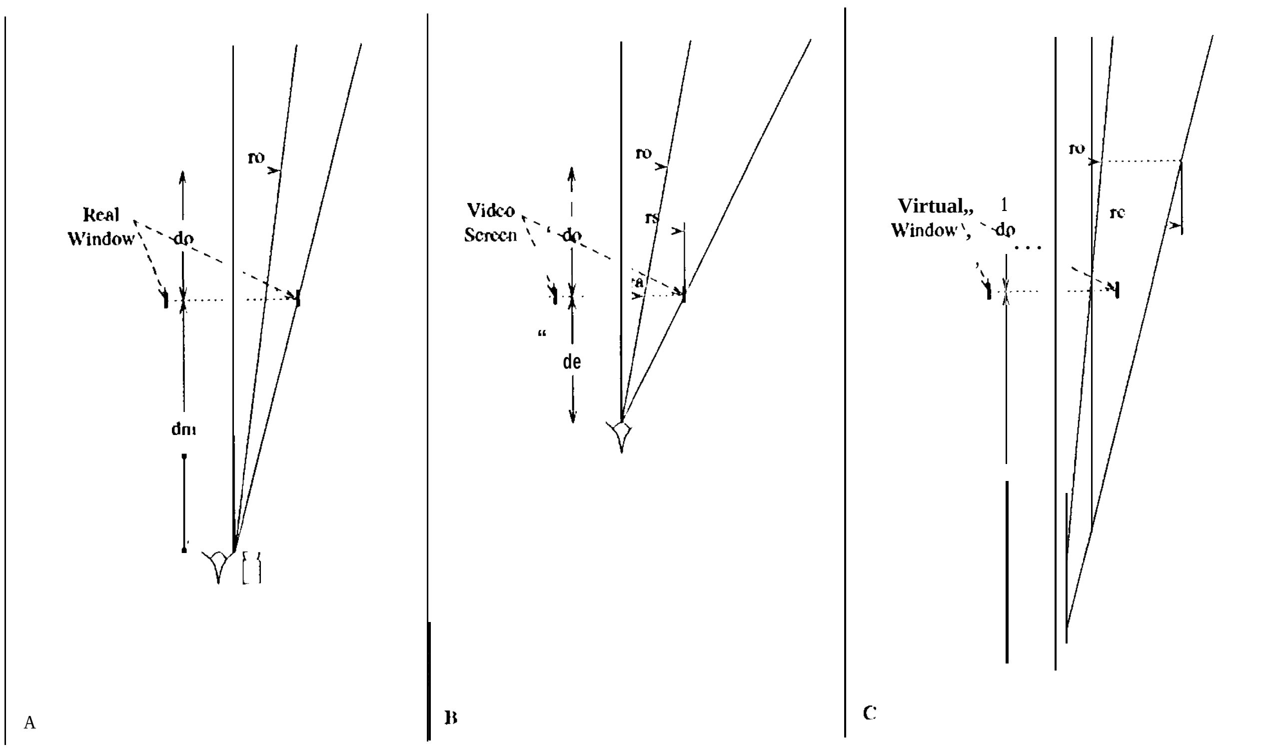

Figure 3: Position mapping

The apparent size of the object is a function of distance from the eye to the screen:

$$r_a = \frac{d_e r_o}{d_e + d_o} \tag{3}$$

The area a camera with field of view (7) will image is a function of' the distance from the camera to the virtual window:

$$r_c = (d_e + d_o)\tan(\gamma) \tag{4}$$

We can simplify this equation by noting that the field of view of the camera matches the angle subtended by a real window the size of the video screen (Figure 3A) at a distance *(d,),)* or:

$$\tan(\gamma) = \frac{r_s}{d_m} \tag{5}$$

Substituting, we get:

$$\frac{\frac{d_c r_a}{d_c + d_o}}{r_s} = \frac{r_o}{\frac{(d_c + d_o) r_s}{d_m}} \tag{6}$$

Solving this for camera distance we get:

$$d_c = \frac{d_m d_o}{d_c} + d_m - d_o \tag{7}$$

We use equation 7 to map each component of the measured head position vector to the desired end effector position vector. This position vector and the previously calculated rotation matrix specify the desired end effector frame relative to the virtual window.

When head tracking is initiated, the position of the virtual window in the world (${}^{V}_{W}F$) is established relative to the initial end effector (camera) frame (${}^{E}_{W}F$) according to:

$$ {}^{V}_{W}F = {}^{E}_{W}F_0 \, {}^{E}_{V}F^{-1} \tag{8}$$

For each subsequent sampling period the desired end effector frame is calculated as:

$$ {}^{E}_{W}F = {}^{V}_{W}F \, {}^{E}_{V}F \tag{9}$$

3 DISCUSSION

This system is an example of non-immersive telepresence. An immersive system would use a head-mounted display (HMD) or multiple large screens to surround the operator. The advantage of this technique is that it does not interfere with the operator seeing and using other components of the control console. It is much less encumbering than an HMD because the operator only need wear the LCD shutter glasses, and they need not be removed while using other part of the system. in an Head-mounted system, the operator must remove the HMD, often a large and heavy device, to use displays and controls that are not part of the immersive environment. The advantages over a surround system are its compactness and simplicity. For this application a feeling of total immersion is not required.

This implementation is unique in that it uses both video images and viewpoint positioning. Most video systems only control pan, tilt and sometimes roll angle of the cameras based on operator head tracking. Graphical environment systems usually map head position to view point one to one. The problem with these systems is that they create an apparent motion of the environment as the operator rotates their head that does not occur in the real world. To look to the right using these systems you must turn your head to the right and look back at the monitor to the left with your eyes. If you want to look away from the monitor, for example to look at another display, you will create an unexpected and confusing shift in the virtual environment. This problem comes from trying to map the immersive domain to a non-immersive display. This virtual window system produces a stable virtual display that behaves intuitively. It is especially useful when you want to preserve a viewpoint but need to look away to operate another control.

4 FUTURE PLANS

This system represents the initial implementation of a virtual window system. We plan to do experiments to determine if and to what extent the system is beneficial compared to manual control of the robot. We will II]ca.sure the time required to examine the flaw and the operators ability to detect flaw characteristics such as flaw depth. We will also explore the operators subjective impressions of the ease of usc of and preferences for the system.

The current implementation dots a good job of producing the correct viewpoint and minimizing object size distortions to produce the illusion of looking through a real window. Future implementations might include camera focal length control to account for relative monitor distance as well as image processing (warping) to account for oblique viewing of the monitor screen as the operator moves around it. High bandwidth communication between the operator console and the robot would be valid for ground robotic inspection systems that do not have the time delays associated with space teleoperation. Each of these would enhance the operators feeling of telepresence.

5 ACKNOWLEDGEMENTS

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